

AD-A101 056 ARMY ELECTRONICS RESEARCH AND DEVELOPMENT COMMAND WS--ETC F/6 20/6
TURBULENCE EFFECTS ON OPEN AIR MULTIPATHS.(U)

UNCLASSIFIED MAY-81 W R WATKINS, K O WHITE, L J CROW
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TURBULENCE EFFECTS ON OPEN AIR MULTIPATHS

MAY 1981

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ASL-TR-0086	2. GOVT ACCESSION NO. AD-A101056	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) TURBULENCE EFFECTS ON OPEN AIR MULTIPATHS		5. TYPE OF REPORT & PERIOD COVERED R&D Final Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Wendell R. Watkins, Kenneth O. White, Laura J. Crow		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS US Army Atmospheric Sciences Laboratory White Sands Missile Range, NM 88002		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS DA Task No. 61101A 17161101A91A, 00 24500
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Electronics Research and Development Command Adelphi, MD 20783		12. REPORT DATE May 1981
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		13. NUMBER OF PAGES 18
		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Open air multipath Gas concentration monitor Turbulence		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The possible effects of turbulence on the maximum usable pathlength of an open air multipath were investigated. Open air multipaths can be used in conjunction with scanning optical sources to measure trace gases along open air optical paths for field testing of military electro-optical systems including high energy lasers. Turbulence was found to be the major source of system degradation for an open air optical multipath. The effects of turbulence on beam spreading as a function of position along the multipath		

20. ABSTRACT (cont)

were measured. Multipath optics image and diffuse the input beam in a beam conserving fashion in producing the multipath. Turbulence has its strongest degrading effects on the diffused beams in the multipaths, thus open air multipaths would require turbulence shielding of this portion of the optical path to be effectively used, especially during high daytime turbulence levels. Such systems can, however, be easily used in enclosed building environments without any path shielding. ←

PREFACE

The authors acknowledge Donald L. Walters for his assistance in the experimental setup and analysis of the turbulence measurements made during this investigation as well as his review of this report.

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INTRODUCTION

Atmospheric gases are major contributors to the degradation of high energy laser (HEL) beams and are significant contributors to the degradation of electro-optical (EO) systems. To compare test results with model predictions for such Army and Department of Defense systems, an accurate characterization of the atmosphere during the testing is required; in particular, a measure is needed of the concentrations of the contributing gas species comprising the atmosphere. When one is concerned with situations in which unknown gases may be contributing to the absorption of the radiation, rapid identification of the gases and determination of their concentrations require use of techniques involving a tunable spectral source, such as a Fourier transform spectrometer (FTS) or a diode laser. Spectrophone systems are not well suited for use with the above spectral sources because they are low power sources and hence degrade the spectrophone's sensitivity. One of the most sensitive means of determining the gas species and concentrations is the use of tunable sources to scan absorption lines characteristic of the various gases. The energy propagates through a long optical path in a test environment such as the long folded optical path produced by the White-type optics¹ of a multipath absorption cell opened to the environment. There is, therefore, a need to investigate what the limits are on open air multipaths used in such measurements.

At the Atmospheric Sciences Laboratory (ASL), White-type absorption cells have been used substantially and their operation has also been improved.²⁻⁶ Two factors have been found to severely limit the maximum usable pathlengths. One is system vibration caused by ground movement, for example, from the proximity to vehicular traffic or winds which can cause the mirror mounts to sway. This effect can be minimized if the mirrors are mounted relatively close to the ground (1/2- to 1-m elevation at most). A second and more pronounced effect is that of temperature gradients along the path or equivalently, in the open

¹John U. White, 1942, "Long Optical Paths of Large Aperture," J Opt Soc Am, 32:285

²Kenneth O. White et al, 1978, "Water Vapor Continuum Absorption in the 3.5 - 4.0 μm Regions," Appl Opt, 17:2711

³Wendell R. Watkins et al, 1979, "Pressure Dependence of the Water Vapor Continuum Absorption in the 3.5 - 4.0 μm Region," Appl Opt, 18:11494

⁴Wendell R. Watkins et al, 1979, "Water Vapor Absorption Coefficients at HF Laser Wavelengths (2.64 - 2.93 μm)," Appl Opt, 18:1582

⁵Wendell R. Watkins, 1976, "Path Differencing: An Improvement to Multipass Absorption Cell Measurements," Appl Opt, 15:16

⁶Wendell R. Watkins and Richard G. Dixon, 1979, "Automation of Long-Path Absorption Cell Measurements," Rev Sci Instrum, 50:86

air multipath, atmospheric turbulence. As a result, the effect of turbulence on an open air multipath has been investigated by using White optics to determine the feasibility of using such optics in a quasi-point gas sampler capacity.

EXPERIMENTAL APPROACH

A set of 20-m White optics from an old longpath absorption cell greatly facilitated the investigation. The set of three spherically concave mirrors could easily be mounted (completely open to the laboratory environment) in the end sections of the old absorption cell. As a first crude assessment of how well the absorption cell optics would work in an open air environment, an He-Ne laser source was used with the White optics to produce a multipath of more than 1 km (25-spot multipath). A pathlength of 1 km is a reasonable estimate of the absorbing path required to measure the species and concentrations of absorbing gases which can significantly affect the propagation of HEL and EO systems. Details of how the multipaths are obtained with White-type optics are given elsewhere.^{5,6} Under room air turbulence, degradation of the output beam was comparable in terms of beam expansion, jitter, and wander to the degradation experienced in a sealed (evacuatable) absorption cell. This was indeed satisfying; for if a long pathlength could not be established in an enclosed room with low turbulence level, then it would be impossible to use the White optics in a field environment.

Initially the plan was to develop and implement a scheme in the laboratory to measure beam degradation and turbulence level produced by an artificial turbulence source and then take the White optics outdoors and investigate the effects of open air turbulence on the multipath beam. For these tests a visible He-Ne laser was used even though most of the source wavelengths of interest are in the near infrared. The wavelength dependence of the turbulent beam spread is slight, $\propto \lambda^{-1/5}$. The results of the laboratory calibration measurements were such that only measurements of field turbulence levels were required to determine the effects on the multipath beam. Hence, the White optics did not have to be taken to a field site.

The general setup for making measurements in the laboratory is shown in figure 1. A 15-mW Spectra-Physics 124B He-Ne laser was used as the source. The He-Ne beam was directed by using two flat mirrors so as to just miss the edge of the White optics' mirror M2 and be centered on mirror M1. Filters to adjust the intensity of the beam as well as apertures to eliminate unwanted

⁵Wendell R. Watkins, 1976, "Path Differencing: An Improvement to Multipass Absorption Cell Measurements," Appl Opt, 15:16

⁶Wendell R. Watkins and Richard G. Dixon, 1979, "Automation of Long-Path Absorption Cell Measurements," Rev Sci Instrum, 50:86

⁷D. L. Fried, 1966, "Limiting Resolution Looking Down Through the Atmosphere," J Opt Soc Am, 56:1380

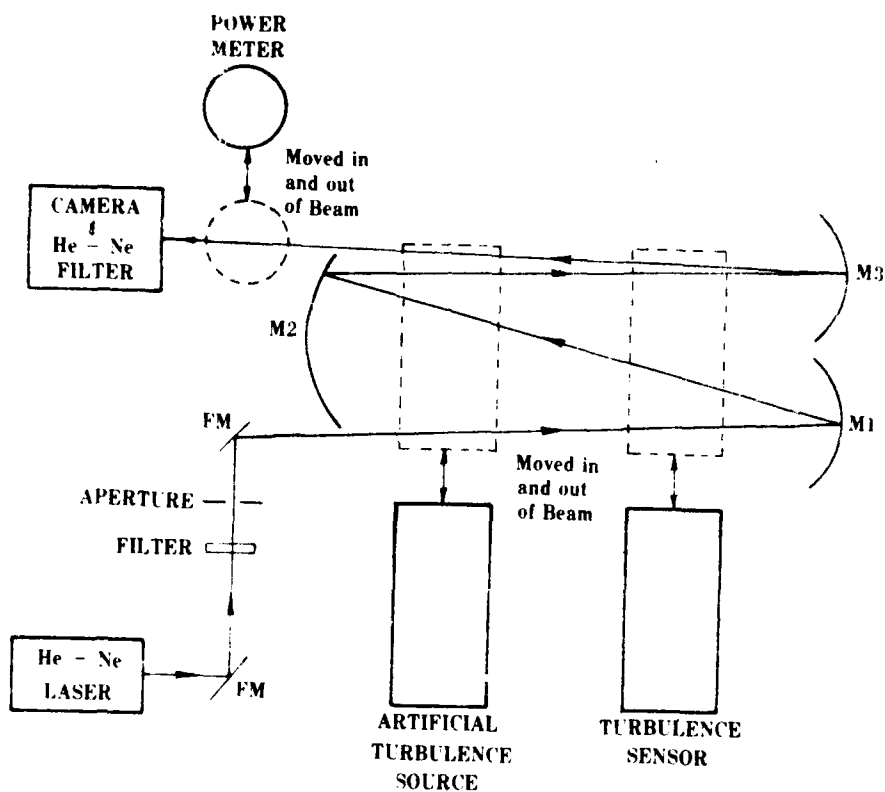


Figure 1. Experimental setup for measuring effects of optical turbulence on an open air multipath. An He-Ne laser was used and with 20-m White-type multipath cell mirrors M1, M2, and M3. The He-Ne input beam was tailored by using a filter, aperture, and flat mirrors. A camera and power meter were used to monitor the He-Ne output beam. Artificial turbulence could be introduced and monitored in the multipath beam.

secondary beams were inserted in the beam before it entered the White optics. The three mirrors which comprise the White optics are spherically concave with radius of curvature and separation distance of 20 m. Mirror M1 directs the beam to a position close to the edge of mirror M2. Mirror M2 then directs the beam to the center of mirror M3. Finally, M3 either directs the beam back to M2 or off the edge of M2 to form the output beam of the multipath. By rotating M3 about the axis normal to figure 1, the pathlength can be changed. The intensity of the output beam can then be monitored or photographed to determine beam degradation caused by turbulence. Figure 1 shows a top view of this He-Ne beam configuration throughout which the beam is approximately 1/2 m above the laboratory floor.

Several sets of measurements were performed. First, the beam size was monitored through time exposure photographs with ambient room turbulence as a function of time of day. Next, an artificial heat source was moved along the multipath to determine the general effects of high turbulence levels. The most pronounced effect occurred near mirrors M1 and M3. A variac was used to change the power level, and the maximum pathlength (i.e., no beam clipping, corresponding to a beam < 6 mm in diameter) was determined for several turbulence levels. Concurrently for a fixed level of turbulence, 45 percent on the variac, the output beam size of a fixed 160-m multipath for a constant output intensity was measured as a function of the position of the turbulence source between mirror M2 and mirrors M1 and M3. Finally, the turbulence levels in the laboratory, as well as outside under cloudy and clear conditions as a function of height above the ground, were measured.

Measurements

The measurement of the change in output beam size as a function of variations in the room air turbulence throughout the day required a substantial amount of initial setup. The He-Ne laser beam had to be adjusted by using mirrors to enter the White optical system. The three 20-m White-type mirrors were rectangular (which does not give the optimum configuration). The mirrors were adjusted to give a multipath output for which the pathlength could be changed by rotating only mirror M3 as is described in detail elsewhere.^{5,6} A Tektronix C-12 oscilloscope camera with the lenses removed was used to photograph the output beam. A narrow bandpass He-Ne filter was used to eliminate background light. Several tests were performed to determine an appropriate time exposure (5 s) and beam intensity which could be adjusted by inserting filters into the beam before the beam entered the White optics. Several problems were encountered in the system setup. To obtain a clear single-image output beam, the filters had to be tilted to diverge secondary beams away from the primary; and apertures were inserted to remove ghost

⁵Wendell R. Watkins, 1976, "Path Differencing: An Improvement to Multipass Absorption Cell Measurements," Appl Opt, 15:16

⁶Wendell R. Watkins and Richard G. Dixon, 1979, "Automation of Long-Path Absorption Cell Measurements," Rev Sci Instrum, 50:86

images before the beam entered the White optics. Tissue paper was inserted into the beam to obtain a diffuse speckle pattern for a cell output to precisely align the camera and filtering system.

This setup was used in photographing the output beam as a function of time of day. The beam size did not noticeably change throughout the day or from day to day, indicating that room air turbulence had little effect on the system. This finding was later verified by measuring the turbulence level in the laboratory along the beam and throughout the day with a C_T^2 probe described below. The laboratory turbulence was indeed low and stable, changing little throughout the day or along the White optics multipath as long as the laboratory doors were closed and activity in the room was kept to a minimum. After the technique for monitoring the change in size of the output beam had been developed, the effects of artificially induced turbulence were investigated. A 125-W heat lamp was mounted in an insulated box 0.4 m on a side. This arrangement produced a hot chimney which could be placed under the multipath anywhere between the mirrors of the White-type optical system. A variac was used to vary the artificial turbulence levels. The most pronounced effect of the artificial turbulence was seen when the source was situated under the multipath near the two-mirror-end of the White optics. To see how much effect the artificial turbulence had, the box was centered 1.44 m from the two mirrors and the variac setting was changed. The maximum usable pathlength was determined for each variac setting used. The turbulence corresponding to the various variac settings was then measured with a calibrated C_T^2 probe (figure 2, obtained from Donald L. Walters of the ASL). Basically the probe consists of two 3-W, 120-V light bulb filaments mounted 20 cm apart on a rigid stand plus the associated electronics for obtaining an integrated dc output voltage which corresponds to a measure of C_T between the probes. Complete details of the operation of the probes are given elsewhere.* The amount of turbulence C_N^2 present can easily be obtained from the values of C_T or the output voltage. A calibration plot is given in figure 3.

After the maximum pathlength was measured for a fixed location of the turbulence and for magnitude of the artificial turbulence source, the beam spread was measured for a fixed pathlength 160 m, for fixed turbulence level (45 percent on the variac), and for varying source positions along the multipath. Because this method of measurement required the comparison of

*Kenneth Kunkel et al, 1979, "Atmospheric Conditions at the High Energy Laser System Test Facility (HELSTF), White Sands Missile Range (WSMR), New Mexico, August 1977 to October 1978, Part I: Optical Turbulence, Wind, Temperature, Net Radiation, and Synoptic Weather Conditions," ASL-DR-79-0004, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM

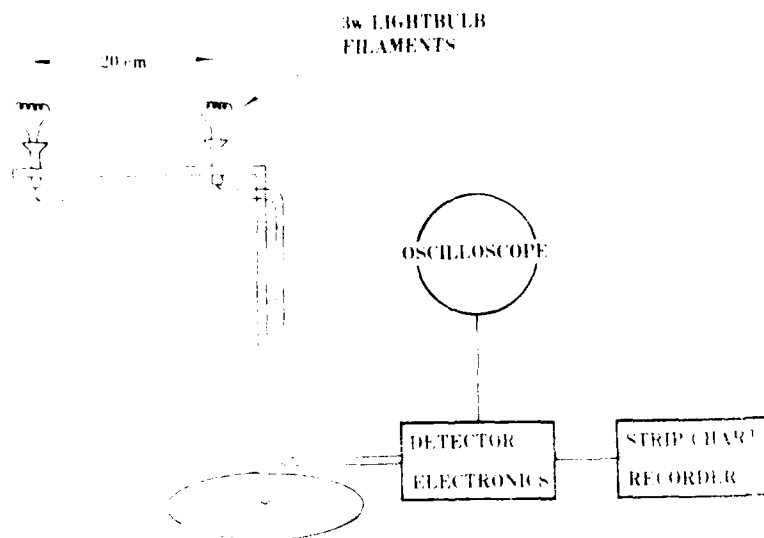


Figure 2. Schematic of the ΔT temperature probe used for measuring thermal response. The two exposed 3-W light bulb filaments are separated by 20 cm.

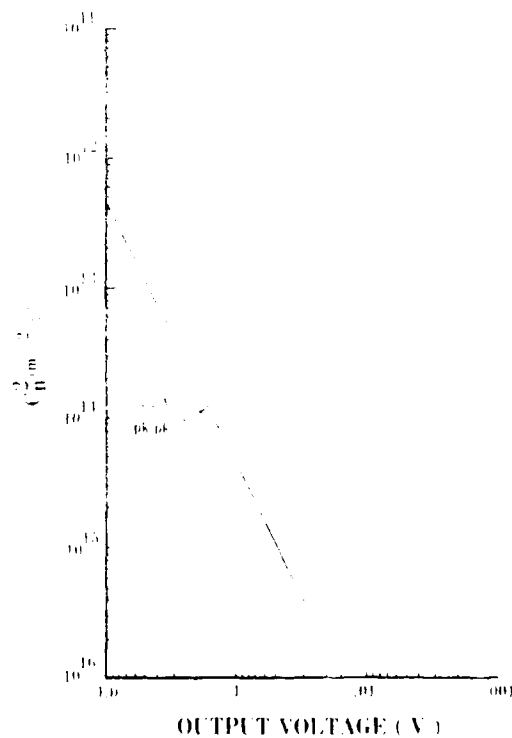


Figure 3. Calibration curve for the thermal probe ΔT sensor.

photographs to determine beam size, additional optics and instrumentation were needed. Two polarizing plates were used in the output beam to adjust the beam intensity. A power meter could be inserted into the beam to monitor the power level. For each position of the artificial turbulence source, the polarizers were rotated to obtain a constant He-Ne power output for each measurement.

Finally, the turbulence probe was taken outside to measure typical turbulence levels during a hot summer day. The probe was used at 1/2- and 1-m elevations and for clear and cloudy conditions.

Measurement Results

It was mentioned earlier that the White optics used were not the best design. The mirrors were rectangular, which is especially bad for mirror M2 (figure 1). The usual technique of getting the input and output beams past mirror M2 is to notch both sides of the upper half of the mirror, thus allowing the bottom row of images to start directly below the edge of the input notch.⁵ Use of a rectangular mirror for M2 required the first image spot on M2 to be positioned closer to the middle of the mirror than with a notched mirror. This positioning causes the maximum obtainable pathlengths to be substantially reduced because the problem of clipping on mirror edges is enhanced. Thus some qualitative judgment had to be used in assessing what defined the maximum usable pathlength.

Clipping of the output beam was noted when the output beam diameter was increased due to the artificial turbulence by a little more than 50 percent over the room air turbulence diameter. The maximum usable pathlength was defined as the longest pathlength for which beam clipping did not occur. With the artificial turbulence source centered 1.44 m from mirrors M1 and M3 and variac settings of 15, 30, 45, 60, 75, and 90 percent, the maximum usable pathlength was determined. The results of these measurements are shown in figure 4. The C_T probe was then used to determine the C_N^2 turbulence level for the variac settings. The output voltage of the C_T probe was found to be quite linear with variac setting (figure 5), having a 0.137-V offset corresponding to C_N^2 for room air turbulence of $8.7 \times 10^{-15} \text{ m}^{-2/3}$. Note that the input beam was 4 mm in diameter and spherically diverged to about 2.0 cm over the 20 m between M2 and mirrors M1 and M3. Mirrors M1 and M3 focused the beam to 4 mm under room air turbulence.

The next step in assessing how turbulence affects the multipath formed by the open air White optics was to fix the pathlength at 160 m (or eight traversals between the mirrors), fix the artificial turbulence level at 45 percent or a value of C_N^2 of $3.5 \times 10^{-12} \text{ m}^{-2/3}$, and vary the location of the turbulence

⁵Wendell R. Watkins, 1976, "Path Differencing: An Improvement to Multipass Absorption Cell Measurements," Appl Opt, 15:16

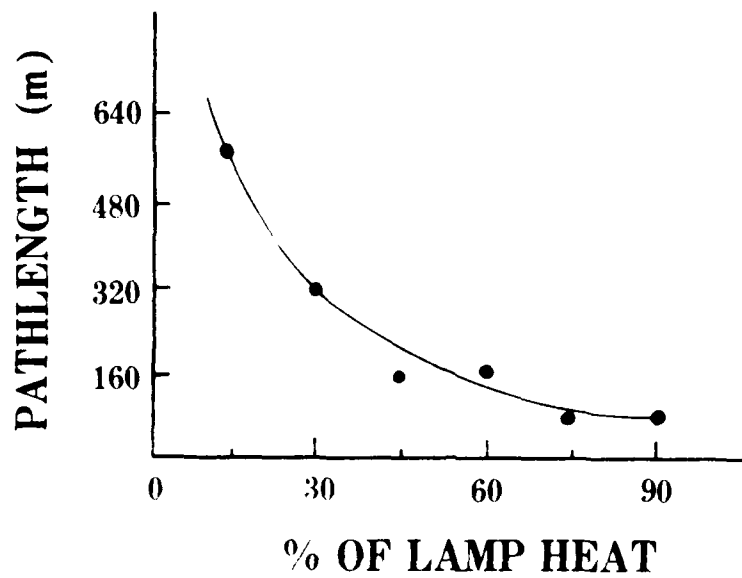


Figure 4. Maximum pathlength as a function of increased artificial turbulence at the two-mirror-end of the multipath.

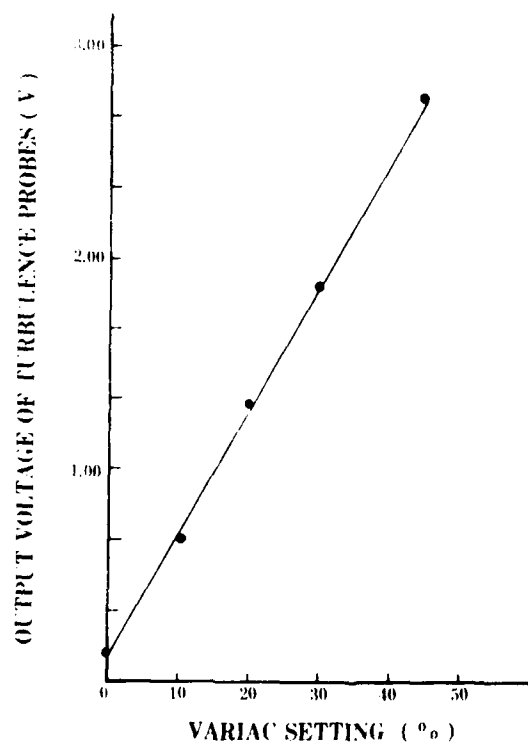


Figure 5. Linearity of turbulence level in the multipath in terms of probe output voltage with respect to artificial source turbulence in terms of variac power setting.

source along the multipath to determine the functional dependence of turbulence location on amount of beam spread. As described earlier, this step was accomplished by comparing 5-s exposure photographs of the He-Ne beam. A pair of polarizers was placed in the output beam; and for each turbulence location, the polarizers were rotated to give a total cell output power of 0.4 mW. Photographs were then taken with the power meter removed, and the beam diameter was measured by averaging the width and height of the central maximum of the beam since the beam was slightly irregular in shape on the photographs. The average of three data runs for ten path locations for the turbulence source is shown as circles in figure 6 with the solid curve representing an eyeball fit to the data. The figure shows substantially more beam spreading as the turbulence is moved closer to the double mirror end of the multipath. Some of this spreading dependence can be accounted for by the fact that the beam is spherically diverging between mirror M2 and mirrors M1 and M3.

The final measurement was to determine turbulence levels in the real atmosphere. Measurements had already been made for high summer turbulence levels at 5-m and 32-m elevations as shown in figure 7. At midday the C_N^2 turbulence level reaches $10^{-14} \text{ m}^{-2/3}$ for 32 m and $10^{-13} \text{ m}^{-2/3}$ for 5-m elevation. Further measurements were needed for this study since the White optics can be situated between only 1/2 and 1 m above the ground without causing serious vibrations problems. Consequently, the C_T^2 temperature probe was taken outdoors to obtain values corresponding to midday turbulence levels for clear and cloudy conditions at 1/2- and 1-m elevations. The measurement results are shown in table 1.

An attempt was made to calculate the maximum usable pathlength as a function of turbulence levels, but this approach presented some very serious theoretical problems, and it became clear that to obtain solutions to these problems (if possible) was completely beyond the scope of this work effort. Therefore, no theoretical discussion will be given. In the conclusions which follow, insight gained during the attempt at analytical understanding is included.

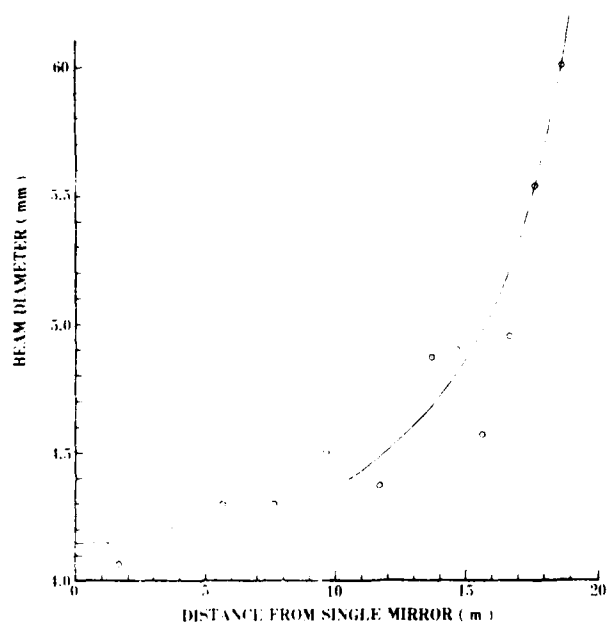


Figure 6. Functional dependence of the effects of output beam spread in terms of beam diameter and location of artificial turbulence source along the 160-m multipath as measured from the single-mirror-end.

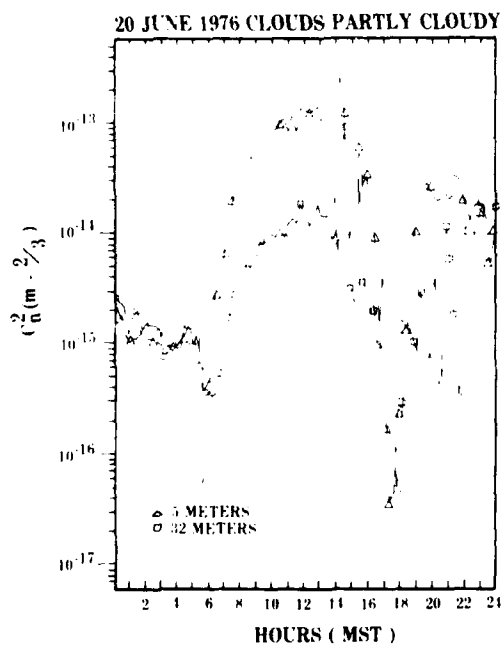


Figure 7. Hourly thermal turbulence measurements of C_N^2 at WSMR for elevations of 5 m (triangles) and 32 m (squares). Data obtained from Glenn B. Hoidale et al. "Micro-Meteorological Measurements for Electro-Optical Propagation Tests at White Sands Missile Range," Proceedings of the Optical-Submillimeter Atmospheric Propagation Conference, 1, 6-9 December 1976.

TABLE 1. TYPICAL OUTDOOR TURBULENCE LEVELS MEASURED AT WSMR

Sky Conditions	Elevation (m)	Average C_N^2 ($m^{-2/3}$)
Clear	1/2	1.3×10^{-12}
Clear	1	7.3×10^{-13}
Cloudy	1/2	1.3×10^{-13}
Cloudy	1	5.7×10^{-14}

CONCLUSIONS

The present investigation has provided much insight into the peculiarities of the White optics multipath. From the data shown one can see that real-world atmospheric turbulence levels are comparable to those levels artificially induced in the laboratory. Usable pathlengths will thus be less than 500 m under clear sky conditions; hence, such a system would not be particularly useful. Although White-type optics cannot simply be taken to a field site and used with an FTS or diode laser to measure gas concentrations and species, they can be employed under enclosed experimental conditions such as a large building. For the first time, the weighting function of turbulence on beam spread as a function of position between the end mirror has been measured (figure 6). Sufficient experimental data could not be obtained within the allotted time frame to feasibly define the functional dependencies; however, enough definition was obtained to establish that, without shielding the two-mirror-end of the multipath, the nominal open air turbulence level so severely degrades the maximum usable pathlength that the measurement scheme will not work. Fortunately, the measurements also lead to a possible solution to the problem because the effects of shielding the two-mirror-end of the multipath could be assessed without extensive field measurements. Shielding the last 3 m of the 20-m optical system used appears to be sufficient to allow a kilometer usable multipath to be established even during the high midday turbulence on clear summer days at White Sands Missile Range.

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